

# Identifying spatial patterns of erosion for use in precision conservation

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**Abstract:** The application of site-specific conservation practices requires knowledge of spatial patterns in fields. This study evaluated two methods of delineating soil erosion patterns in a central Iowa field. First, soil erosion rates of individual grid based samples were estimated using soil displacement of cesium-137 ( $^{137}\text{Cs}$ ). Second, tillage and water erosion were estimated using the topography-driven Water and Tillage Erosion Model (WATEM). The tillage erosion map showed soil loss in convex shoulder positions and soil accumulation in concave footslope and toeslope landscape positions. Alternately, water erosion was associated with slope severity and slope length on backslopes. When the tillage and water erosion map patterns were combined a good correlation with the  $^{137}\text{Cs}$  soil erosion pattern was graphically and statistically exhibited. Study results suggest that tillage erosion be included with water and wind erosion estimates when developing spatial maps that reflect a field's erosion history. Spatial maps depicting a field's erosion history and the primary processes affecting erosion could be used for site-specific implementation of conservation practices such as cover crops, organic matter additions, and no-till, which could be targeted at specific erosion processes.

**Keywords:** Erosion, precision agriculture, soil conservation, tillage

**A major challenge to crop producers throughout the world is determining how to conserve soil resources while optimizing production in fields with landscapes prone to soil erosion.** Having the ability to identify spatial patterns of erosion and the processes causing those patterns would help crop producers optimize profitability while sustaining soil resources. During the past two decades, tillage erosion (the net movement of soil downhill during tillage operations) has received increased recognition as a soil degradation factor (Veseth, 1986; Govers et al., 1999). Consequently, soil erosion patterns within agricultural fields can be seen as the result of wind, water and tillage processes.

Soil redistribution by tillage is a significant factor in creating within-field soil variation (Schumacher et al., 1999; Van Oost et al., 2003; De Alba et al., 2004). Soil redistribution by tillage is a function of tillage intensity and slope gradient. In tillage erosion the net soil loss or gain is governed by the change in slope gradient, (the curvature of the land surface), (Lindstrom et al., 1992). However, a

distinction between tillage erosion and tillage translocation needs to be explained. Tillage translocation is the movement of soil by tillage. Tillage erosion is caused by tillage translocation when slope gradients change. For example, on a uniform slope, soil import will equal soil export during tillage operations. However, individual soil particles will have been moved from their original location. When slope gradients change along the path of a tillage operation, soil import will not equal soil export, consequently tillage erosion/deposition occurs with a net loss or gain of soil mass.

Two categories of tillage erosion need to be distinguished. They are 1) tillage erosion due to a change in slope (loss from convex areas and deposition in concave areas), and 2) tillage erosion/deposition due to the effect of field boundaries (Van Oost, et al., 2000). An example of the effect of field boundaries in the Palouse region of the Pacific Northwest is given in Papendick and Miller (1977) where 3 to 4 m (10 to 13 ft) soil banks have been formed by repeated downhill plowing above

and below permanent field boundaries. A detailed numerical description of tillage erosion is given in Appendix A.

**Cesium-137 ( $^{137}\text{Cs}$ ) soil erosion estimation.** Medium term (~40 yr) soil erosion can be estimated with  $^{137}\text{Cs}$  to obtain a spatial assessment of total erosion within a landscape and to quantify estimates of soil erosion associated with wind, water, and tillage processes (Ritchie and McHenry, 1990; Quine et al., 1997; Walling and He, 1999). Cesium-137 is a radionuclide with a half life of approximately 30 years that was extensively deposited during the 1950s and 1960s from atmospheric testing of nuclear weapons. Atmospheric fallout of  $^{137}\text{Cs}$  was strongly adsorbed to fine soil particles upon contact making it an effective tracer of soil movement (Ritchie and McHenry, 1990). A comparison between  $^{137}\text{Cs}$  levels at local undisturbed reference sites with those in nearby cultivated fields can be used to estimate total soil erosion/ deposition for the medium term (~40 yr). Increased  $^{137}\text{Cs}$  indicates soil deposition (gain) while decreases reflect soil erosion (loss). Measurements of  $^{137}\text{Cs}$  from an individual soil profile core can provide an estimate of soil erosion at a point location. Consequently, multiple  $^{137}\text{Cs}$  soil core samples taken across a landscape can be used to quantify spatial erosion patterns and to validate spatially distributed models of soil erosion (Walling and He, 1999). A more complete discussion about

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using  $^{137}\text{Cs}$  to derive soil erosion rates can be found in Ritchie and McHenry, (1990) and Walling and He, (1999).

In the early 1990s,  $^{137}\text{Cs}$  was used to determine spatial erosion/deposition patterns in closed and open watersheds within the Palouse region of the Pacific Northwest and to compare net soil erosion measurements with Revised Universal Soil Loss Equation (RUSLE) estimates (Busacca et al., 1993; Montgomery et al., 1997), RUSLE estimates the average annual soil loss from interrill and rill water erosion. In these studies, tillage movement was identified as a contributor to total soil erosion as estimated by resident  $^{137}\text{Cs}$ , but its magnitude was not estimated. The study by Montgomery et al. (1997) concluded that tillage movement rates and the reliability of RUSLE factors needed to be known to accurately compare RUSLE and  $^{137}\text{Cs}$  soil erosion estimates.

In southwestern Ontario, Canada, Lobb and Kachanoski (1999) noted that high rates of soil loss in upper slope positions were inconsistent with predicted patterns of soil erosion as determined by wind or water erosion models such as RUSLE (Renard et al., 1997). In an erosion study on shoulder slope positions, Lobb et al. (1995) determined that tillage erosion accounted for at least 70 percent of the total soil loss as estimated by resident  $^{137}\text{Cs}$ . Subsequently, Lobb and Kachanoski (1999) demonstrated that tillage erosion modeling could account for the severe soil loss on convex soil landscape positions in upland landscapes in southwestern Ontario. Lobb and Kachanoski (1999) also noted that tillage erosion can mask the effects of water erosion by deposition of soil from upslope positions. This may be an issue of concern to those trying to understand landscape soil erosion patterns in Midwestern states, such as Iowa, where severe spring storms and water erosion are not uncommon.

Other studies using  $^{137}\text{Cs}$  to assess soil erosion and landscape redistribution include pioneering work by Quine et al. (1994) and Govers et al. (1996) who used resident  $^{137}\text{Cs}$  estimates of total erosion to examine the contributions of water and tillage erosion on agricultural land in Western Europe.

**Water and Tillage Erosion Model (WATEM).** WATEM is a spatially distributed water and tillage erosion model that can be used to predict patterns of soil erosion (Van Oost et al., 2000). The WATEM model has been used in Western Europe to compare

water and tillage erosion estimates with total soil erosion rates ( $^{137}\text{Cs}$  derived measurements). It is a topography-driven model that requires a digital elevation model to run water and tillage components. The water erosion component of WATEM was adapted from RUSLE to estimate deposition as well as soil erosion in two dimensional landscapes. WATEM implements RUSLE through dialog options for direct entry of the R, K, C, and P factors in the RUSLE equation (Appendix B). WATEM replaces the L factor with the unit contributing area, i.e. upslope drainage area per unit of contour length (Desmet and Govers, 1996). The unit contributing area and S factors are derived from a digital elevation model and used to calculate the LS factor based on the selected LS algorithm. The water component of the model also requires input of a transport capacity coefficient ( $K_{Tc}$ ). The transport capacity coefficient is used in the determination of  $T_c$ , the local transport capacity, ( $\text{kg m}^{-1}$ ). The transport capacity in WATEM is estimated by the equation:  $T_c = K_{Tc} * E_{PR}$ , (where  $E_{PR}$  = the potential annual rill erosion). Local deposition occurs if the local transport capacity in a landscape is exceeded by sediment inflow (Van Oost et al., 2000).

Tillage erosion can be mathematically represented by the equation:

(1)

$$E = k_{\text{till}} * d^2h / dx^2$$

where,

E = local erosion/deposition rate ( $\text{kg m}^{-2}$ )

h = height at a given point of the hillslope (m)

x = horizontal distance (m)

$k_{\text{till}}$  = tillage transport coefficient ( $\text{kg m}^{-1}$ )

Govers et al. (1994) and Van Oost et al. (2000). WATEM employs a grid-based numerical method to solve for E. A high quality digital elevation model and entry of a tillage transport coefficient ( $k_{\text{till}}$ ) through a dialog box are needed to run the tillage erosion model. Two-dimensional soil erosion estimates for tillage and water processes are calculated separately in WATEM. A combined tillage-water soil erosion estimate can be developed by summing individual tillage and water erosion rates at the grid level (Van Oost et al., 2000).

Our broad objective for this paper is to compare model estimates of spatial patterns of tillage and water erosion with total soil erosion estimates for a central Iowa field that has

been in a corn-soybean rotation continuously since 1957. Specific objectives include: 1) Determine spatial patterns of erosion and deposition that developed from 1957 to 2003 for a field representing hilly topography in central Iowa by using  $^{137}\text{Cs}$  soil profile measurements; 2) Use the WATEM model to compare predicted soil erosion patterns for water and tillage processes and their combined effect to estimates derived from the  $^{137}\text{Cs}$  measurements.

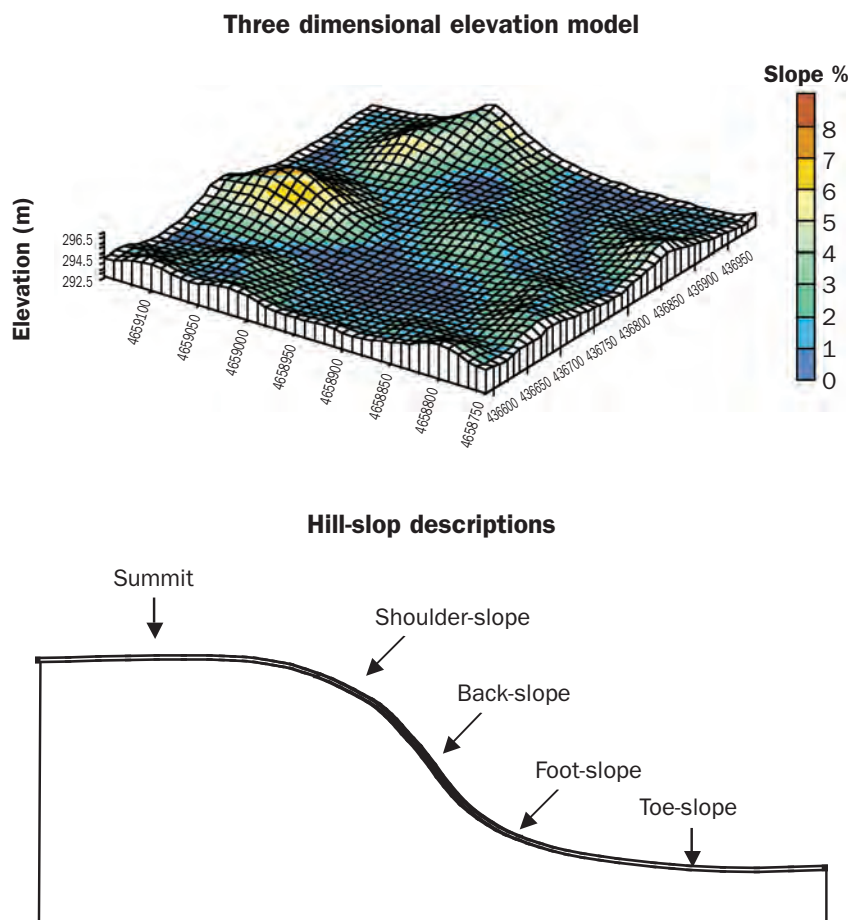
## Methods and Materials

**Site description and background.** Tillage, water, and  $^{137}\text{Cs}$  erosion modeling was performed on a 12 ha (30 ac) field area contained within a 16 ha (40 ac) research field in central Iowa (near Ames, Iowa). The field contains several small closed depressions, one large depression, and is tile drained without surface inlets. Surface water accumulates and remains in the closed depressions for several days following high volume precipitation. Soils in the field were formed in calcareous glacial till and are classified as the Clarion (fine-loamy, mixed, mesic Typic Hapludolls) - Nicollet (fine-loamy, mixed, mesic Aquic Hapludolls) - Webster (fine-loamy, mixed, mesic Typic Haplaquolls) soil association. Detailed information on the soils can be found in Steinwand and Fenton (1995) and Steinwand et al. (1996). A two-year corn-soybean rotation has been followed since 1957. Moldboard plowing, disking and harrowing were the principal tillage operations from 1934 through 1981. The field has been chisel plowed, disked, or left undisturbed (soybean years) in the fall following harvest since 1981. Shortly before planting one or two passes with a field cultivator and/or harrow are used to incorporate herbicides if desired and to prepare the final seedbed.

A precision digital elevation model was developed during the spring of 1999 using a geodetic grade carrier-phase DGPS receiver. Elevation data were collected on 4.5 m (15 ft) spaced transects approximately every 4 m (13 ft). Initial positioning reliability was +/- 0.03 m in the horizontal plane and +/- 0.06 m (2.4 in) in the vertical plane. A 10 by 10-m (33 by 33ft) digital elevation grid map, created by kriging the elevation data using Surfer (Golden Software Inc, 1999), was developed for subsequent erosion modeling. A three dimensional elevation model of the field, overlain with contoured slope, is displayed in Figure 1.

**Figure 1**

The research field is depicted in a three dimensional elevation model overlaid with a contour map of slope (%). Hill-slope profile descriptions are also shown with corresponding location.



**WATEM parameterization.** Water and tillage input parameters of WATEM are specified below for the study site. A 10 m by 10 m (33 by 33ft) digital elevation model of the study area provided topography input for the WATEM water and tillage components. The WATEM tillage and water soil erosion estimates were output as Surfer grid files with units ( $\text{kg m}^{-2} \text{yr}^{-1}$ ). The grid files were multiplied by 10 at the grid point level using Surfer to convert erosion output units to ( $\text{t ha}^{-1} \text{yr}^{-1}$ ). Surfer grid math was used to combine the tillage and water grid files into a single tillage-water erosion grid file. Tillage and water erosion estimates were then determined for  $^{137}\text{Cs}$  sample locations using ArcView GIS 3.2 (ESRI, 1999).

**Water model settings.** The RUSLE water erosion factors were determined using R, C, and P factor settings available for Boone County, Iowa from the U.S. Department of Agriculture Natural Resources Conservation

Services (USDA-NRCS) electronic Field Office Technical Guide. The K factor was determined using the online NRCS Soil Data Mart for Boone County, Iowa. The Nearing option (Nearing, 1997) was selected as the LS algorithm to be used by WATEM.

Input settings:

$R = 150$  (metric input:  $0.255 \text{ MJ mm m}^{-2} \text{h}^{-1} \text{yr}^{-1}$ )  
- rainfall-runoff erosivity factor

$K = 0.25$  (metric input:  $32.5 \text{ kg m}^2 \text{h m}^{-2} \text{MJ}^{-1} \text{mm}^{-1}$ )  
- soil erodibility factor

$LS =$  Derived from digital elevation model  
- slope length & slope steepness

$C = 0.31$  (1957-1981:  $C \sim 0.37$ ,  
1981-2003:  $C \sim .25$ )  
- cover - management factor

$P = 1$

-support practice factor

LS Algorithm Option: Nearing; slope length exponent: (rill = interrill)

Transport capacity coefficient  $kT_c = 170 \text{ m}$   
- (Picked by inspection using the  $kT_c$  value (174.4 m) as a starting base (Van Oost et al., 2000).

**Tillage model settings.** Two inputs are required for the tillage component of WATEM; a digital elevation model (to compute slope changes) and a tillage transport coefficient ( $k_{\text{till}}$ ). The tillage transport coefficient was based on the field's tillage history from 1957 to 2002. An average yearly tillage transport coefficient was estimated using implement  $k_{\text{till}}$  values extracted from a table compiled by Van Muysen et al. (2000). Table 1 provides a list of tillage transport coefficients used to estimate the average  $k_{\text{till}}$  value

Tillage operations: 1957 to 1981: Moldboard Plow, Disk ( $k_{\text{till}}$ :  $715 \text{ kg m}^{-1}$ )

Tillage operations: 1981 to 2003: Chisel Plow, Disk, Harrow ( $k_{\text{till}}$ :  $722 \text{ kg m}^{-1}$ )

Average Tillage Transport coefficient ( $k_{\text{till}}$ ):  $718 \text{ kg m}^{-1} \text{yr}^{-1}$  ( $482 \text{ lb ft}^{-1} \text{yr}^{-1}$ )

**Cesium-137 erosion estimates.** In May 2003, three soil samples were collected from the 0 to 30 cm (0 to 12 in) layer at each location on a 25-m (82 ft) grid in the field using a 3.2 cm (1.25 in) diameter push probe. The three samples were combined for analysis. Deeper soil samples were collected from the 30 to 50 cm (12 to 20 in) layer at locations where deposition had obviously occurred. Soil profile samples were also collected in 5-cm (2 in) increments to a depth of 1-m at selected locations to measure the depth distribution of  $^{137}\text{Cs}$ . Cesium-137 sample locations are shown in (Figure 2).

Reference soil samples were collected in areas where no apparent soil redistribution had occurred since the mid 1950s and used to determine baseline  $^{137}\text{Cs}$  input to the area. Six reference locations were collected within 2 km (1.24 mi) of the study field.

All soil sample locations were surveyed with a code based geographic positioning system (GPS) (Trimble Geoexplorer XT<sup>1</sup>) and are accurate to approximately one meter.

The composite soil samples were dried, sieved to pass through a 2-mm screen, and placed in Marinelli beakers and sealed for  $^{137}\text{Cs}$  analyses. Analyses for  $^{137}\text{Cs}$  were made by gamma-ray analysis using a Canberra

**Table 1.** Tillage transport coefficients are listed for tillage erosion modeling of the study site.

| Source               | Till depth (m) | Tillage speed (m s <sup>-1</sup> ) | Implement   | Tillage transport coefficient (k <sub>till</sub> ) (kg m <sup>-1</sup> ) |
|----------------------|----------------|------------------------------------|-------------|--|
| Lobb et al. (1999)   | 0.17           | 2.66                               | Chisel plow | 275  |
| Lobb et al. (1999)   | 0.23           | 1.71                               | Moldboard   | 346  |
| Lobb et al. (1999)   | 0.17           | 0.84                               | Tandem disc | 369  |
| Mech and Free (1942) | 0.12           | —                                  | Harrow      | 78   |

Table extracted from (Van Muysen et al., 2000)

Genie-2000 Spectroscopy System (Canberra Industries, Meriden, CT) that receives input from three Canberra high purity coaxial

germanium crystals (HpC >30 percent efficiency) into 8192-channel analyzers. The system is calibrated and efficiency determined

using an Analytics (Atlanta, Georgia) mixed radionuclide standard (10 nuclides) whose calibration can be traced to U.S. National Institute of Standards and Technology. Measurement precision for <sup>137</sup>Cs is ± 4 to 6 percent.

Soil redistribution (erosion or deposition) rates and patterns were calculated for each soil sample location based on the <sup>137</sup>Cs concentrations in the soil and models that convert <sup>137</sup>Cs measurements to estimates of soil redistribution rates (Walling and He, 1999; 2001; Ritchie and McHenry, 1990). The Mass Balance Model 2 (Walling and He, 2001) that uses time-variant <sup>137</sup>Cs fallout input and consideration of the fate of freshly deposited fallout was used to calculate soil redistribution rates. Sample locations with less <sup>137</sup>Cs than the <sup>137</sup>Cs at the reference locations are assumed to be eroding while locations with more <sup>137</sup>Cs than the <sup>137</sup>Cs reference locations are assumed to be deposition sites. A plow depth of 25 cm (10 in) was used to convert <sup>137</sup>Cs activity to erosion/deposition rates. Surfer was used to produce a two dimensional spatial map for erosion/deposition (t ha<sup>-1</sup> yr<sup>-1</sup>) based on the erosion estimates derived from each <sup>137</sup>Cs sample site.

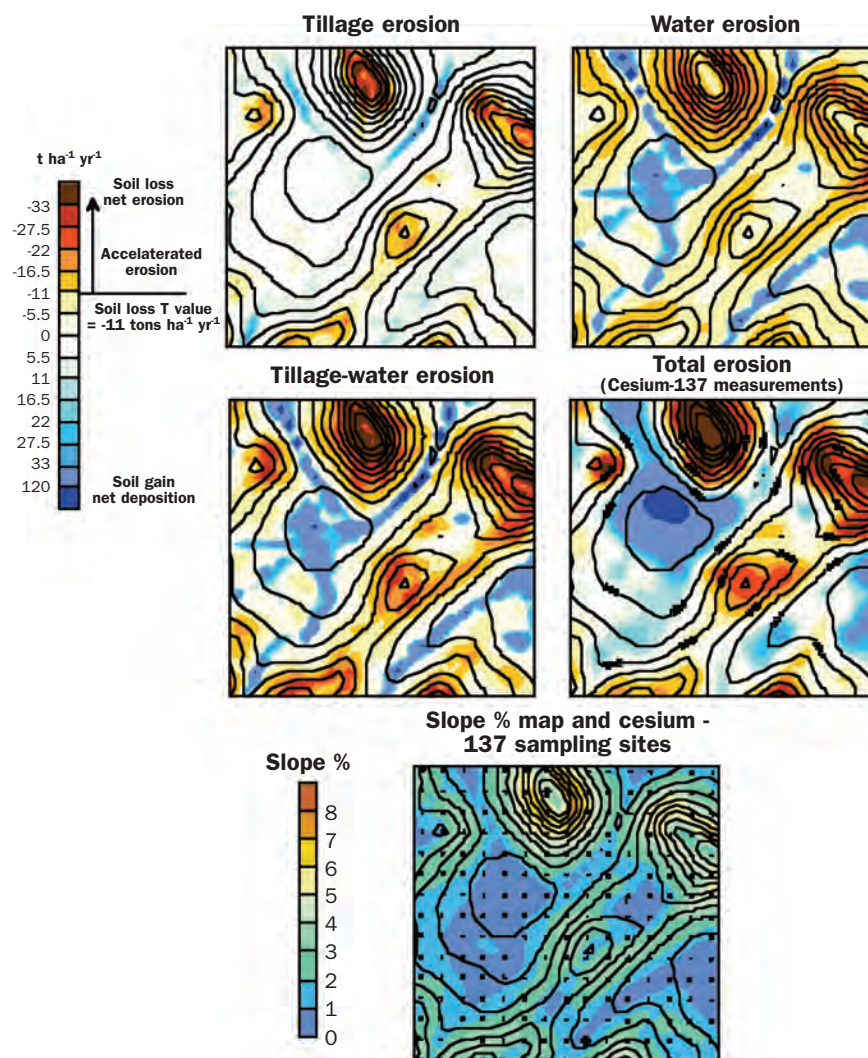
## Results and Discussion

First spatial patterns of estimated tillage, water, tillage-water and total erosion (<sup>137</sup>Cs measurements) are described for the years 1957 to 2003. Then, tillage and water erosion estimates are compared with total erosion (<sup>137</sup>Cs) estimates at each sampling site.

**Spatial patterns of erosion.** *Tillage erosion.* The spatial pattern for tillage erosion shows a net loss in soil occurring on the convex landscape positions with soil accumulation in concave positions with little change in positions with uniform or linear slopes (Figure 2). Tillage erosion rates from the convex landscape positions exceeded the soil tolerance limit of 11 t ha<sup>-1</sup> yr<sup>-1</sup> (5 t ac<sup>-1</sup> yr<sup>-1</sup>) for 12 percent of the field with maximum erosion rates of 44 t ha<sup>-1</sup> yr<sup>-1</sup> (20 t ac<sup>-1</sup> yr<sup>-1</sup>). Tillage translocation between slope positions with uniform slopes (small changes in slope gradi-

**Figure 2**

Erosion patterns developed from tillage, water, tillage-water and total erosion (<sup>137</sup>Cs) modeling of the research field are displayed. Cesium-137 sampling sites are also displayed on a contour map of slope percent for the field.



Elevation contour lines are overlaid on all maps  
Elevation labels are shown only on total erosion map

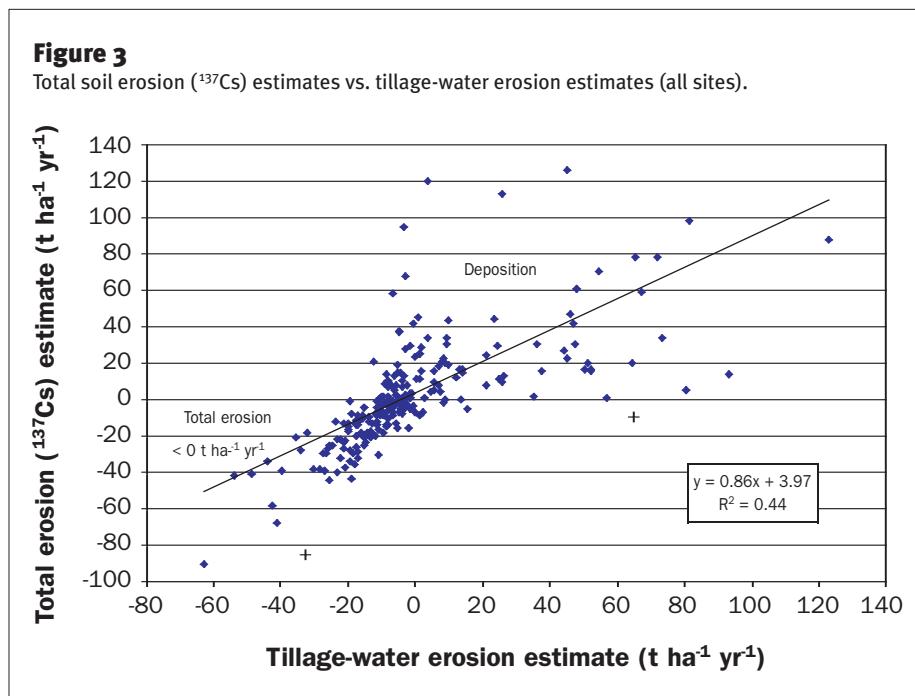
ent) acted as a mechanism of soil particle transport with exported soil particles being replaced in equal amounts by soil import. If tillage travel, over the same piece of land, is assumed to switch directions each year; the net affect will be individual soil particles being transported downslope with minimal net mass soil loss on uniform slopes. This phenomenon explains how excessive net soil loss from tillage erosion at the shoulder of a hill (convex) is balanced by soil deposition at the footslope (concave position) and not at the backslope of a hill (Figure 1).

**Water erosion.** The spatial pattern for water erosion, dictated by the RUSLE inputs, shows a soil loss in landscape positions as a function of slope length and slope gradient with maximum erosion estimates occurring in the positions with the steepest slope gradients (Figure 2). Local deposition occurred when the local transport capacity within the landscape was exceeded by sediment inflow. Water erosion rates from the eroded landscape positions exceeded the soil tolerance limit of  $11 \text{ t ha}^{-1} \text{ yr}^{-1}$  ( $5 \text{ t ac}^{-1} \text{ yr}^{-1}$ ) for 31 percent of the field with a maximum erosion rate of  $32 \text{ t ha}^{-1} \text{ yr}^{-1}$  ( $14.3 \text{ t ac}^{-1} \text{ yr}^{-1}$ ).

Soil redistribution limitations for water processes in the field included: 1) the lack of information on deposition/erosion contributions from overland flow entering the field from outside the boundaries of the study area; 2) the ponding effect of standing water in the closed depressions in the field and how it influenced sediment redistribution in the lower field elevation areas.

**Combined tillage and water erosion.** The spatial pattern for combined tillage and water erosion shows the effect of adding tillage erosion estimates from convex hilltop locations to water erosion estimates on side slopes (Figure 2). The combined erosion estimates increased the severity of soil loss in upper hill slope positions; while tillage deposition in lower concave positions either decreased erosion estimates or increased deposition estimates from water processes.

Tillage-water erosion estimates from the eroded landscape positions exceeded the soil tolerance limit of  $11 \text{ t ha}^{-1} \text{ yr}^{-1}$  ( $5 \text{ t ac}^{-1} \text{ yr}^{-1}$ ) for 36 percent of the field with tillage-water erosion rates exceeding  $60 \text{ t ha}^{-1} \text{ yr}^{-1}$  ( $27 \text{ t ac}^{-1} \text{ yr}^{-1}$ ) in the most erodible landscape positions. Additionally, when tillage and water erosion rates were combined 12.5 percent of the field exceeded  $22 \text{ t ha}^{-1} \text{ yr}^{-1}$  ( $10 \text{ t ac}^{-1} \text{ yr}^{-1}$ ) as compared with 3.5 percent for either



water or tillage erosion individually.

**Total erosion based on  $^{137}\text{Cs}$  measurement.** The spatial pattern for total erosion based on  $^{137}\text{Cs}$  measurements reflects all erosion processes including the processes of tillage, water and wind (Figure 2). In this study, total erosion ( $^{137}\text{Cs}$ ) was compared only with tillage and water erosion estimates derived with WATEM. A visual comparison of total and tillage-water erosion spatial patterns shows that the total erosion ( $^{137}\text{Cs}$ ) spatial patterns closely follow the field's topographic features in the same way as does the pattern of combined tillage and water erosion. The main difference between the spatial patterns was a larger area of deposition on the total erosion ( $^{137}\text{Cs}$ ) map as compared with the combined tillage-water erosion map.

Total erosion ( $^{137}\text{Cs}$ ) estimates exceeded the soil tolerance limit of  $11 \text{ t ha}^{-1} \text{ yr}^{-1}$  ( $5 \text{ t ac}^{-1} \text{ yr}^{-1}$ ) for 31 percent of the study area compared with 36 percent for tillage-water erosion estimates. Total erosion ( $^{137}\text{Cs}$ ) rates exceeded  $60 \text{ t ha}^{-1} \text{ yr}^{-1}$  ( $27 \text{ t ac}^{-1} \text{ yr}^{-1}$ ) in the most erodible landscape positions, similar to the maximum rates found by the tillage-water erosion model. Total erosion ( $^{137}\text{Cs}$ ) estimates greater than  $22 \text{ t ha}^{-1} \text{ yr}^{-1}$  ( $10 \text{ t ac}^{-1} \text{ yr}^{-1}$ ) comprised 15 percent of the study area which compares favorably with 12.5 percent for tillage-water erosion modeling estimates.

The main discrepancies in erosion estimates between the two models could possibly be improved by incorporating wind erosion estimates for the upper hillslope positions where total erosion ( $^{137}\text{Cs}$ ) estimates are more

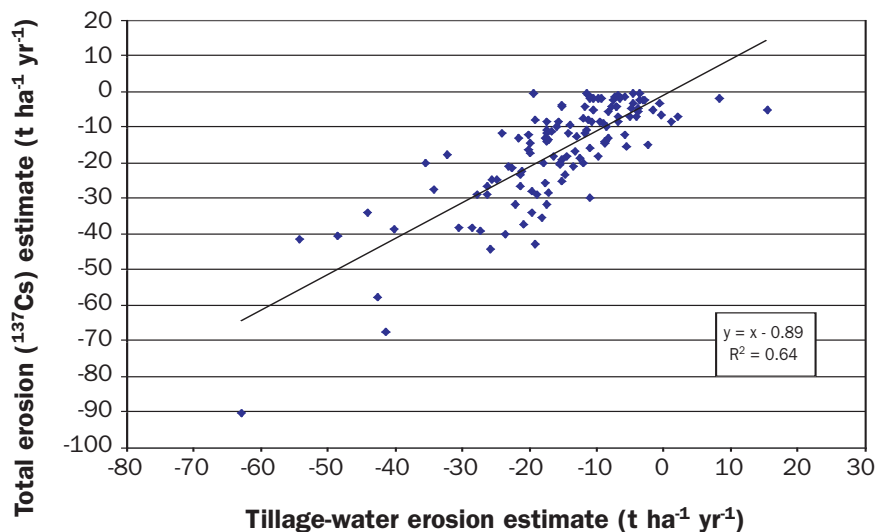
severe. Tillage soil translocation, as opposed to tillage erosion, may also account for some of the discrepancy in these positions. In the lower elevations of the field the effect of ponding water and overland flow originating from outside the study area boundaries may help explain some of the erosion/deposition differences between the total and tillage-water erosion estimates.

**Sample location comparison of erosion rates.** Estimates of soil erosion from all WATEM derived erosion maps were paired with total erosion estimates at  $^{137}\text{Cs}$  sampled locations. Linear regression analysis was conducted on each paired data set with total soil erosion ( $^{137}\text{Cs}$ ) estimates as the dependent variable. A graph of Total vs. Tillage-Water Erosion, ( $r^2 = 0.44$  for all sites) (Figure 3), depicts a scattered relationship between total and tillage-water erosion estimates when total erosion ( $^{137}\text{Cs}$ ) estimates are depositional ( $> 0$ ). Possible reasons, for the scattered relationship, include the effect of water ponding in depressions, overland flow contributions from outside the study area influencing erosion/deposition in the low lying areas, and modeling limitations.

To limit linear regression analysis to the non-depositional areas within the study site, total erosion ( $^{137}\text{Cs}$ ) estimates ( $< 0$ : non-depositional) were used to define the data set population (Figure 4). Linear regression coefficients for all the paired data sets with total soil erosion ( $^{137}\text{Cs}$ ) estimates as the dependent variable are displayed in Table 2. In the study area, medium-term ( $\sim 40 \text{ yr}$ )

**Figure 4**

Total soil erosion ( $^{137}\text{Cs}$ ) estimates vs. tillage-water erosion estimates. The data set population was the  $^{137}\text{Cs}$  sampling sites with total erosion estimates (non-depositional). Two outliers with large residual values were removed from the data set (outlier positions are identified in Figure 2 and 3 with + symbol). One  $^{137}\text{Cs}$  sample was situated in a low lying portion of the field where concentrated water flow may have created a disproportionate measurement. A second  $^{137}\text{Cs}$  sample occurred in a transitional area near the top of a hill summit.



estimates of total soil erosion ( $^{137}\text{Cs}$ ) (non-depositional) were best estimated by the combined tillage-water erosion model with an  $r^2$  value of 0.64 as opposed to an  $r^2$  value of 0.31 when estimated by water erosion

alone or an  $r^2$  value of 0.46 when estimated by tillage erosion alone.

The two sample Kolmogorov-Smirnov test (Steel et al., 1997) (KS-test) was used to determine if model predictions of soil loss at

eroding sampling points differed significantly from soil loss estimated using  $^{137}\text{Cs}$ . KS-test results indicate that the  $^{137}\text{Cs}$  soil erosion data set ( $^{137}\text{Cs}$  estimates  $< 0$ ) did not differ significantly from the paired tillage-water erosion data set ( $p = 0.402$ ), while individual water and tillage erosion data sets paired with the  $^{137}\text{Cs}$  soil erosion data set were significantly different ( $p < 0.004$  and  $p < 0.001$ , respectively). Mean values for soil loss ( $\text{t ha}^{-1} \text{ yr}^{-1}$ ) at eroding sampling points were 16.5 for the  $^{137}\text{Cs}$  erosion data set, 15.6 for the tillage-water erosion data set, 11.8 for the individual water erosion data set, and 3.8 for the individual tillage data set. When examining depositional sampling points ( $^{137}\text{Cs}$  estimates  $> 0$ ) all data sets were significantly different from each other. This was expected since the spatial location of deposition is only generally accounted for in the WATEM modeling approach.

Individual contributions of tillage and water erosion to combined tillage-water erosion estimates are shown in Table 3 for sample sites classified by zones of total erosion ( $^{137}\text{Cs}$ ). The contribution of tillage erosion to averaged tillage-water erosion estimates by zone was 25 percent ( $>11$  and  $< 22$ ), 33 percent ( $>22$  and  $<33$ ) and 46 percent ( $>33 \text{ t ha}^{-1} \text{ yr}^{-1}$ ) ( $15 \text{ t ac}^{-1} \text{ yr}^{-1}$ ).

**Table 2. Linear regression coefficients are shown for estimating total erosion ( $^{137}\text{Cs}$ ) rates when water, tillage and tillage-water erosion estimates are the independent variable.**

| Dependent variable                  | Independent   | Slope | Constant ( $\text{t ha}^{-1} \text{ yr}^{-1}$ ) | $r^2$ | N sites | Standard error of the estimate ( $\text{t ha}^{-1} \text{ yr}^{-1}$ ) |
|-------------------------------------|---------------|-------|---|-------|---------|---|
| Total erosion ( $^{137}\text{Cs}$ ) | Tillage-water | 1.0   | - 0.89  | 0.64  | 123     | 8.9   |
| Total erosion ( $^{137}\text{Cs}$ ) | Tillage       | 1.12  | -12.3   | 0.46  | 123     | 6.6   |
| Total erosion ( $^{137}\text{Cs}$ ) | Water         | 1.37  | -0.36   | 0.31  | 123     | 5.0   |

The data set population was determined by sampling sites with total erosion rates (non-depositional).

**Table 3. Total erosion ( $^{137}\text{Cs}$ ) is compared to tillage and water erosion estimates by zone. Erosion zones are categorized according to total erosion ( $^{137}\text{Cs}$ ) samples. Total, tillage-water, and individual tillage and water erosion estimates are averaged for sample values contained within each zone. According to  $^{137}\text{Cs}$  erosion estimates 55 percent of the field was non-depositional.**

| Erosion zone ( $\text{t ha}^{-1} \text{ yr}^{-1}$ ) | Total erosion zone average ( $\text{t ha}^{-1} \text{ yr}^{-1}$ ) | Tillage-water erosion zone average ( $\text{t ha}^{-1} \text{ yr}^{-1}$ ) | Water erosion zone average ( $\text{t ha}^{-1} \text{ yr}^{-1}$ ) | Tillage erosion zone average ( $\text{t ha}^{-1} \text{ yr}^{-1}$ ) | Percent field |
|---|---|---|---|---|---------------|
| $>33$   | 44.8  | 34.3  | 18.4  | 15.9  | 7             |
| 33 to 22  | 26.9  | 21.3  | 14.2  | 7.1   | 8             |
| 22 to 11  | 16.0  | 15.9  | 11.8  | 4.1   | 16            |
| 11 to 0   | 5.0   | 7.9   | 9.0   | 1.1 (deposition)  | 24            |
| (Percent field total)                               |   |   |   |   | 55            |

The data set population was determined by sampling sites with total erosion rates (non-depositional).

## Summary and Conclusion

In this study,  $^{137}\text{Cs}$  was used as a tracer of soil particle redistribution over a 12 ha (30 ac) field site with one large and several small closed depressions. The terrain of the field reduced soil particles being transported out of the study area with most of the runoff being collected in the low areas of the field. Medium term (~40 yr) soil erosion and deposition estimates that integrated all erosion processes were derived using  $^{137}\text{Cs}$  soil measurements. WATEM (Water and Tillage Erosion Model) (Van Oost et al., 2000) was used to estimate soil erosion rates due to tillage and water processes. Spatial patterns of estimated tillage, water, tillage-water and total erosion ( $^{137}\text{Cs}$  measurements) were developed for the years 1957 to 2003. Examination of the spatial patterns revealed that total erosion ( $^{137}\text{Cs}$ ) patterns closely followed the topographic features associated with the combined effects of tillage and water erosion. Spatial pattern maps also revealed that combining tillage and water erosion estimates not only expanded the extent of erosion but also increased its severity in upslope positions. The contributions of tillage and water erosion were evaluated by comparison to total soil erosion ( $^{137}\text{Cs}$ ) estimates for the medium-term (~40 yr) (Table 2). Linear regression analysis revealed estimates of total soil erosion ( $^{137}\text{Cs}$ ) at non-depositional sampled locations were best estimated by the combined tillage-water erosion model with an  $r^2$  value of 0.64 as opposed to an  $r^2$  value of 0.31 for water erosion or an  $r^2$  value of 0.46 for tillage erosion.

The  $^{137}\text{Cs}$  soil erosion data set (non-depositional) did not significantly differ with corresponding combined tillage-water values but did significantly differ with individual water and tillage erosion data sets. Tillage and water erosion estimates were thus shown to provide a more accurate reflection of total field erosion when used in concert as opposed to individually. Modeling dissimilarities in deposition estimates were possibly a result of several factors including ponding water, overland flow from outside the study boundaries and modeling limitations.

Modeled erosion rates when compared to a soil tolerance limit of  $11 \text{ t ha}^{-1} \text{ yr}^{-1}$  ( $5 \text{ t ac}^{-1} \text{ yr}^{-1}$ ) revealed tillage erosion exceeded the limit in 12 percent of the field, water erosion (31 percent), tillage-water erosion (36 percent), and  $^{137}\text{Cs}$  estimated erosion (31 percent). Erosion estimates greater than  $22 \text{ t ha}^{-1} \text{ yr}^{-1}$  ( $10 \text{ t ac}^{-1} \text{ yr}^{-1}$ ) were exceeded by  $^{137}\text{Cs}$

erosion modeling in 15 percent of the field, combined tillage-water erosion (12.5 percent), tillage erosion (3.5 percent), and water erosion (3.5 percent). Sample sites were classified by zones of total erosion ( $^{137}\text{Cs}$ ) to multiples of the soil tolerance limit. The contribution of tillage erosion to averaged tillage-water erosion estimates within those zones was 25 percent (>11 and <22), 33 percent (>22 and <33) and 46 percent (>33  $\text{t ha}^{-1} \text{ yr}^{-1}$  or  $15 \text{ t ac}^{-1} \text{ yr}^{-1}$ ).

Study results reflect the importance of tillage erosion as a contributor to field erosion estimates as improved erosion pattern and data set comparison to non-depositional total erosion ( $^{137}\text{Cs}$ ) estimates were achieved when tillage and water erosion estimates were combined. Tillage erosion also contributed substantially to water-tillage erosion estimates measured above the soil tolerance limit. The influence of predicted tillage erosion on the landscape of this field suggests that improved understanding of the dynamic interactions of tillage erosion with water and wind erosion deserves more recognition and research. Improved knowledge of the interactions of soil movement by not only water and wind but also tillage processes would be of great benefit in the development of spatial maps that reflect all the processes of erosion that occur within a field.

**Application.** Spatial patterns of past erosion are descriptive of changes in soil properties that relate to crop productivity (Lowery et. al., 1995). Accurate maps of a field's soil erosion history/tendencies could be used to infer differences in yield potential and soil degradation potential within landscapes. A detailed spatial knowledge of individual erosion processes (water, wind, tillage), acting within a field, could also be used to target management options. Erosion/deposition pattern maps based on erosion caused by water or tillage could be used to site specifically direct planting and tillage operations. For example, cover crops could be planted only in those zones that are determined to be highly erodible due to water while tillage could be suspended or moderated in zones determined to be highly susceptible to tillage erosion. Conversely, field areas where deposition or water ponding occur may benefit from increased tillage. Just as conservation programs attempt to target funds to regions and fields that are most prone to soil degradation, precision conservation technology allows targeting of specific management

practices to those areas of the field that are most prone to soil degradation. Targeting of conservation practices within the field increases erosion control effectiveness by recognizing that erosion control practices are erosion agent specific and that unnecessary application of these practices can be costly and inefficient.

## Endnote

<sup>1</sup>Trade names are included for the benefit of the reader and do not imply an endorsement of or a preference for the product listed by the U. S. Department of Agriculture, Iowa State University, or South Dakota State University.

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## Appendix A: Estimating tillage erosion (one dimensional example).

The empirical equation for soil displacement by tillage is of the form: (Lindstrom et al., 1992)

$$L = \beta(S) + \alpha$$

where,

L = soil displacement by tillage (m);

S = slope gradient (m m<sup>-1</sup>), positive in the upslope direction, negative in the downslope direction;

α = constant

β = regression coefficient

The soil translocation mass per unit tillage width (T<sub>m</sub>), for a given tillage operation, is described by the equation:

$$T_m = (D^* \rho_b) * L$$

$$T_m = (D^* \rho_b) * \beta(S) + \alpha \quad \text{'units: kg m}^{-1}$$

where,

D = tillage depth 'units (m)

ρ<sub>b</sub> = soil bulk density 'units (kg m<sup>-3</sup>)

L = soil displacement caused by tillage 'units (m)

The net soil loss or gain for tillage erosion (E) at a specified point is derived as follows:

$$E = (T_{m \text{ (in)}} - T_{m \text{ (out)}}) / \Delta x_s = [(D^* \rho_b) * \beta(S_1) + \alpha] - [(D^* \rho_b) * \beta(S_2) + \alpha] / \Delta x_s$$

$$E = (T_{m \text{ (in)}} - T_{m \text{ (out)}}) / \Delta x_s = (D^* \rho_b * \beta) * [(S_1 - S_2)] / \Delta x_s$$

$$E = (-D^* \rho_b * \beta) * [(S_2 - S_1)] / \Delta x_s \quad (1)$$

where,

Δx<sub>s</sub> = the distance between the midpoints of two consecutive slope segments (The distance Δx<sub>s</sub> is measured in the direction of positive soil movement).

S<sub>1</sub> = Slope of first slope segment in adjacent slope segments

S<sub>2</sub> = Slope of second slope segment in adjacent slope segments

T<sub>m (in)</sub> = soil mass per unit width of tillage operation moving into a soil block

T<sub>m (out)</sub> = soil mass per unit width of tillage operation moving out of a soil block

The first slope segment met in the direction of travel is S<sub>1</sub> and the second segment is S<sub>2</sub>.

The factors (-D\*ρ<sub>b</sub>\*β) in Equation 1 can be condensed into a single variable, named the tillage transport coefficient (k<sub>till</sub>), (Govers et al 1994)). The tillage transport coefficient (k<sub>till</sub>) describes the intensity of a tillage operation. Tillage transport coefficients (k<sub>till</sub>) for different tillage operations can be listed in table format (i.e. chisel plow: 275 kg m<sup>-1</sup>, moldboard plow: 346 kg m<sup>-1</sup>, etc.).

The tillage transport coefficient (k<sup>till</sup>) for a given implement is developed under specified soil conditions and tillage speed and defined as k<sub>till</sub> = -D\*ρ<sub>b</sub>\*β.

Substituting k<sub>till</sub> into Equation 1:

$$E = k_{till} * (S_2 - S_1) / \Delta x_s$$

'Net soil loss in direction of soil movement (2)

or,

$$E = k_{till} * d^2 h / dx^2 \quad (3)$$

where,

E = Net soil erosion (kg m<sup>-2</sup>)

h = height at a given point of the hillslope (m)

x = horizontal distance (m)

k<sub>till</sub> = tillage transport coefficient (kg m<sup>-1</sup>)

Tillage soil erosion units (kg m<sup>-2</sup>) multiplied by 10 converts to (t ha<sup>-1</sup>).

## Appendix B. Revised Universal Soil Loss Equation (RUSLE)

RUSLE, used world-wide to estimate soil erosion is based on the relationship:

$$A = R * K * LS * C * P$$

where,

A = estimated average soil loss per unit area

R = rainfall-runoff erosivity factor

K = soil erodibility factor

L = slope length factor

S = slope steepness factor

C = cover - management factor

P = support practice factor